Photonic Band Gap Materials: Engineering the Fundamental Properties of Light

Sajeev John
Department of Physics
University of Toronto
Canada

www.physics.utoronto.ca/~john

Photonic Band Gap (PBG) materials are artificial, periodic, dielectrics that enable engineering of the most fundamental properties of electromagnetic waves. These properties include the laws of refraction, diffraction, and spontaneous emission of light. Unlike traditional semiconductors that rely on the propagation of electrons through an atomic lattice, PBG materials execute their novel functions through selective trapping or “localization of light” using engineered defects within the dielectric lattice. This is of great practical importance for all-optical communications and information processing. Three dimensional (3D) PBG materials offer a unique opportunity for simultaneously (i) synthesizing micron-scale 3D optical circuits that do not suffer from diffractive losses and (ii) engineering the electromagnetic vacuum density of states in this 3D optical micro-chip. This combined capability opens a new frontier in integrated optics as well as the basic science of radiation-matter interactions.

We review recent approaches to micro-fabrication of photonic crystals with a large 3D PBG centered near 1.5 microns. These include direct laser-writing techniques and holographic lithography. We review the concept of a hybrid 2D-3D PBG hetero-structure in which a 2D photonic crystal micro-chip layer is suitably lattice matched and embedded within a 3D PBG material. This microchip layer contains optical wave-guides and optical micro-cavities that enable frequency selective control of spontaneous emission of light from atoms. Unlike traditional wave-guides that confine light in a high refractive index medium using total internal reflection, these air-wave-guides operate using the principle of light localization for confinement of light along a low refractive index path.

We demonstrate a nearly universal approach to ultra-dense, three-dimensional, integrated optics in general 3D PBG architectures. These 3D optical circuit paths are constructed using broadband, loss-less, chip-to-chip interconnects between 2D micro-chip layers, intercalated within the 3D PBG host material. Unlike electronic micro-circuitry, each air-wave-guide path can simultaneously conduct hundreds of wavelength channels of information, throughout the 3D micro-chip.

In addition to exhibiting diffraction-less flow of light through micron-scale bends, this optical micro-chip allows the engineering of very large and abrupt changes in the local electromagnetic density of states as a function of frequency. This leads to unprecedented frequency selective control of spontaneous emission, modification of the blackbody radiation spectrum, and some fundamentally new optical functions unattainable in conventional photonics.

Inverse Design Problems in Electromagnetics and Nano-Photonics

Eli Yablonovitch
UCLA Electrical Engineering Dept., Los Angeles CA 90095-1594

Chiu-Yen Kao, and S. Osher
UCLA Mathematics Dept., Los Angeles CA 90095

Maxwell's equations are to photonic crystals, as Schrodinger's equation is to conventional crystals. Since photonic crystals are purely products of our imagination, the question has always been what is the exact structure that should be fabricated? This is particularly true for 2-dimensional thin photonic crystals, which can be mass-produced in any Silicon foundry. Nevertheless, it is not yet clear what is the exact 2-d structure that would achieve a desired goal.

Engineering design is formally a type of mathematical Inverse Problem. The design goal is a certain electromagnetic specification or desired electromagnetic performance. It is necessary to work backward from that goal to the exact design of the dielectric boundary that achieves that objective. For example, in mathematics, the Level Set Method has emerged[1] as an excellent tool that can contribute to algorithms[2] for the optimization of boundaries and edges.

In the Photonic Crystal field, the era of purely intuitive design may now be obsolete. We must now concentrate more on design software, rational design, and the numerical solution of inverse problems. There are a number of inverse algorithms, including genetic algorithms, the error-propagation method, and simulated annealing, that can contribute to future progress in photonic crystal design. It is expected that the study of photonic crystals will more and more become the study and development of rational inverse design algorithms and software.

Periodic structures sometimes emerge as optimal solutions to a design problem, but not every design problem has a photonic crystal solution. We have queried the software for the ideal 2-d photonic crystal structures to create high lying bandgaps, even up to the 11⇒12 bandgap. The 2-d photonic crystal geometry that emerges from the software is rather exotic, and would have been difficult to find such structures by human trial and error.

We believe that such software will be essential for designing and optimizing the 2-d Silicon nano-photonic circuits that are now becoming available.

[1] Osher, S.J.; Santosa, F. **Level set methods for optimization problems involving geometry and constraints,** Journal of Computational Physics, vol.171, (no.1), Academic Press, 20 July 2001.
Chiu-Yen Kao, S. Osher, and E. Yablonovitch, "**Maximizing Band Gaps in Two-Dimensional Photonic Crystals, using Level Set Methods**", submitted for publication.
[2] S.J. Cox, J. Funct. Anal, 133:30-40,1995
S.J. Cox and D.C. Dobson, SIAM J. Appl. Math, 59:2108-2120, 1999
S.J. Cox and D.C. Dobson, J. Comput. Phys., 158:214-224, 2000
J.M. Geremia, J. Williams, and H. Mabuchi, Phys. Rev. E., 66, 06606, 2002
Yu Chen, Rong Yu, Weifei Li, Nohadani O, Haas S, Levi AFJ. **Adaptive Design Of Nanoscale Dielectric Structures For Photonics**. Journal of Applied Physics, vol.94, no.9, 1 Nov. 2003, pp.6065-8

Recent progresses in 2D photonic crystal slabs—Ultrahigh-*Q* cavities, nano-devices, and spontaneous emission control

S.Noda, B.S. Song, Y.Akahane, H.Takano, M.Fujita, S.Takahashi, Y.Tanaka, and T.Asano

Department of Electronic Science and Engineering, Kyoto University

In this presentation, recent progresses in 2D photonic crystal (PC) slabs will be reviewed based on our works. First of all, progresses in high-*Q* nanocavities in 2D PC slab is explained, where it is shown that the concept of Gaussian confinement [1] and ideas of tuning of air-holes [2] and/or double heterojunctions [3] enable to achieve nanocavities with ultrahigh-*Q* factor of 10^5~10^6 and small modal volume of ~$1(\lambda_0/n)^3$. Next, some examples of progresses in photonic nano devices are explained. The ultrahigh-Qnanocavities and the concept of in-plane hetero structure [4] enable to achieve photonic devices including highly efficient in-plane type channel add/drop filters [5,6] and optical memories [7]. Then, the capability of 2D PC slabs on the control of spontaneous emission is explained. In contrast to 3D photonic crystals [8], 2D photonic crystal slabs have a very interesting feature on the control of spontaneous emission. It is experimentally demonstrated that overall spontaneous emission rate is suppressed by 2D PBG effect, while emission efficiency for the vertical direction is significantly increased [9].

References: [1] Y. Akahane, T. Asano, B. Song, and S. Noda, *Nature* **425** (2003) 944.

[2] Y. Akanane, T. Asano, B. S. Song, and S. Noda, *Optics Express*, **13** (2005)1202.

[3] B.S. Song, S. Noda, T. Asano, and Y. Akahane, *Nature Materials*, 4 (2005) 207.

[4] B.S. Song, S. Noda, and T. Asano, *Science* **300** (2003) 1537.

[5] H. Takano, Y. Akahane, T. Asano, and S. Noda, *APL* **84** (2004) 2226.

[6] Y. Akahane, T. Asano, H. Takano, B. S. Song, Y. Tanaka, and S. Noda, *Optics Express*, **13** (2005) 2512.

[7] Y. Tanaka,T. Asano, and S. Noda, *IQEC/CLEO-PR* (July 2005).

[8] S. Ogawa, M. Imada, S. Yoshimoto, M. Okano, and S. Noda, *Science* 305 (2004) 227 (published online 3 June 2004 (10.1126/science.1097968)).

[9] M. Fujita, S. Takahashi, Y. Tanaka, T. Asano, and S. Noda, *to be published*.

Time Reversal in Metamaterials and Photonic Crystals

J B Pendry
The Blackett laboratory, Imperial College London, UK

The conventional route to time reversal of light pulses is via 4-wave mixing. Two counter propagating beams,

$$\mathbf{k}_1 = +\mathbf{k},\ \omega_1 = \omega, \qquad \mathbf{k}_2 = -\mathbf{k},\ \omega_2 = \omega$$

interact with the signal, $\mathbf{k}_3, \omega$, via a non-linear medium to produce a time reversed signal. One slightly unconventional view is to interpret the process as the signal making a vertical $\Delta\mathbf{k} = 0$ transition between $+\omega$ and $-\omega$. Since the frequency appears in the field equations as ωt, this equivalent to reversing the time.

This interpretation suggests another route to time reversal which is to make a spatially uniform perturbation in the dielectric function of the material through which the pulse is propagating, but with the perturbation confined to a very short time interval.

$$\varepsilon(t) = \varepsilon_{static} + \eta\delta(t - t_0)$$

The perturbation contains all frequency components, but spatial uniformity forbids anything but a $\mathbf{k}$-conserving transition. In a uniform medium this means a transition from $+\omega$ to $-\omega$ thus producing a time reversed signal.

In practice generating such a rapidly change in the dielectric function is impracticable at optical frequencies as the time scale has to be less than $1/\omega$. However in metamaterials and photonic crystals the dispersion relationships are much richer and we shall show how it is possible to effect time reversal using perturbations on a time scale much larger that $1/\omega$ giving new opportunities for the time reversal of pulses ranging from RF to the visible in frequency.

Metal surfaces with holes in them: New plasmonic metamaterials

F. J. García-Vidal

Departamento de Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, E-28049 Madrid, Spain E-mail: fj.garcia@uam.es

Since the pioneering experiment of Ebbesen *et al.* [1] reporting extraordinary optical transmission (EOT) through 2D hole arrays perforated in optically thick silver films, the optical properties of subwavelength apertures has become a very active area of research in electromagnetism. From the beginning, this phenomenon was explained in terms of the resonant excitation of surface plasmons that decorate the two metal-dielectric interfaces. In recent years, we have demonstrated that EOT is a more general phenomenon appearing in, for example, corrugated photonic crystal surfaces [2] or in 1D-structured metal surfaces for *s*-polarization (i.e., without plasmons) [3]. It is clear now that the only ingredients that are necessary in order to observe EOT is the existence of a surface EM mode and a corrugation allowing the coupling of the incident wave to this mode.

Surprisingly, we also found that an array of subwavelength holes in a perfect conductor also gave rise to EOT even though the free surface of an unperforated perfect conductor has no surface modes. We have recently cleared up this paradox [4,5] by showing that corrugation (with holes or dimples or grooves) of perfect conductor surfaces originates surface EM modes with a plasmon-like (so called *spoof* plasmons) behavior. Importantly, the dispersion relation of these *spoof* plasmons is mainly dictated by the geometry of the indentations (size and separation) opening the possibility of tailoring the properties of these modes in order to control the flow of light in the surface of a metal.

References

[1] T.W. Ebbesen, H.J. Lezec, H.F. Ghaemi, T. Thio, and P.A. Wolff, Nature 391, 667 (1998).

[2] E. Moreno, F.J. Garcia-Vidal and L. Martin-Moreno, Phys. Rev. B **69**, 121402(RC) (2004).

[3] E. Moreno, L. Martin-Moreno and F.J. Garcia-Vidal (to be published).

[4] J.B. Pendry, L. Martin-Moreno and F.J. Garcia-Vidal, Science **305**, 847 (2004).

[5] F.J. Garcia-Vidal, L. Martin-Moreno, and J.B. Pendry, J. Opt. A: Pure Appl. Opt. **7**, S97 (2005).

Some subtle details of imaging using a negative refractive medium

C.T. Chan, L. Zhou, Jensen Li
Department of Physics, Hong Kong University of Science and Technology
Hong Kong

We analyzed the time evolution of image formation in 2D and 3D super lenses. The relationship between resolution, absorption, and the time to reach stabilization is quantitatively established with concrete examples. We find significant differences in the time evolution dynamics between 2D and 3D focusing. We find a characteristic image oscillation in two dimensional focusing that is induced by a vortex-like surface excitation with a zero group velocity; while in 3D, image oscillation is inevitable if the real part of effective permittivity and permeability is not exactly -1.

All realizations of meta-materials are through structural resonances and the validity of the theory predictions hinges on the fact (or assumption) that the wavelength under consideration is much larger than the structural length scale so that it is meaningful to talk about an effective permittivity and permeability; and that effective medium provides a good description of the physics of the phenomena, such as imaging. We examine quantitatively how far an effective medium can carry us in the particular case of subwavelength imaging. For that purpose, we construct a model in which the resonanting units can be made as small as we please, and we see that even in that limit, there is a difference between the true system (with microstructure) and that represented by its effective permittivity and permeability.

Lattice, site, and plasmon resonances in structured metal films

F. J. García de Abajo Donostia International Physics Center and Centro Mixto CSIC-UPV/EHU,
San Sebastián, Spain

Structured metallic surfaces display a rich variety of resonances that can be classified into three distinct categories: lattice resonances associated to periodic structures, site resonances originating in localized modes at specific sites, and intrinsic modes like surface plasmons. This classification is illustrated by means of several examples: light transmission through hole arrays, transmission assisted by hopping through buried structures, transmission through holes filled with high-index dielectrics, etc. The interaction between these types of resonances is also discussed. Applications of the above examples will include proposals for perfect light absorbers and invisible metals.

This work has been done in collaboration with J. J. Sáenz, G. Gómez Santos, T. V. Teperik, V. V. Popov, A. B. Borisov, S. V. Shabanov, L. A. Blanco, and R. Gómez Medina.

Topology Optimized Building Blocks for Integrated Photonics

O. Sigmund and J.S. Jensen
MEK, Technical University of Denmark, Building 404, 2800 Kgs. Lyngby, Denmark.

In recent work we have extended and applied the topology optimization method [1] to the synthesis of various building blocks potentially to be used in integrated photonic circuits. The topology optimization method essentially consists in repeated field solutions (finite element analyses of the field equations) and material redistribution steps (free redistribution of dielectric). Typically a few hundred analyses are required for convergence to the optimized solution. So far, we have presented topology optimized solutions for various bends (120, 90 and 60 degrees) which have been experimentally verified to have hitherto unprecedented bandwidths and transmissions. Both TE and TM-polarization bends and splitters have been demonstrated [2-5].

In this paper, we discuss the topology optimization method in more details, we discuss its strengths and weaknesses, and we demonstrate new applications in couplers, tapers, de-multiplexors and others. The method is equally efficient for the synthesis of band gap as for photonic wire based waveguides and we compare the different design formulations for transmission and bandwidth.

[1] M. P. Bendsøe and O. Sigmund, *Topology Optimization*, Springer (2003).
[2] P.I. Borel *et al*., *Optics Express*, **12**, 9, pp. 1996-2001 (2004).
[3] P.I. Borel *et al.*, to appear in *Electron. Lett.* (2005).
[4] L.H. Frandsen *et al.*, *Optics Express*, **12**, 24, pp. 5916-5921 (2004).
[5] J.S. Jensen and O. Sigmund, *App. Phys. Lett.*, **84**, pp. 2022-2024 (2004).

Analytical examination of Fano resonances in photonic crystal devices

S. F. Mingaleev[1,2], A. E. Miroshnichenko[3], Yu. S. Kivshar[3], and K. Busch[1],
[1] Department of Physics and College of Optics and Photonics: CREOL,
University of Central Florida, Orlando, FL 32816, U.S.A.
[2] Bogolyubov Institute for Theoretical Physics, Kiev 03143, Ukraine
[3] Nonlinear Physics Centre and Centre for Ultra-high bandwidth Devices for Optical Systems (CUDOS), Australian National University, Canberra ACT 0200, Australia

Many types of recently suggested photonic crystal devices display specific resonance transmission properties that can be associated with the existence of Fano resonances. The simplest class of such systems is a straight waveguide that is weakly coupled to a side-placed defect or cavity. We show that both linear and nonlinear transmission properties of a number of such optical devices can be accurately studied within the frameworks of the generalized Fano-Andersen discrete model with nonlocal coupling [1]. Based on analytical solutions of this model for several basic types of linear and nonlinear photonic crystal devices, we examine origins of different peculiarities observed in the resonance transmission spectra and emphasize importance of thought-out designs of such devices. We demonstrate how small modifications in the device design can lead to qualitative changes in the resonance transmission spectrum, significantly improving such features as resonance quality factors, bistability thresholds, and tolerances with respect to fabrication disorder.

[1] A. E. Miroshnichenko, S. F. Mingaleev, S. Flach, and Yu. S. Kivshar, *Phys. Rev. E*, in press (2005); arXiv:cond-mat/0412341.